Cosmic muons rejection in ICARUS

Final Report - Summer Students at Fermilab program

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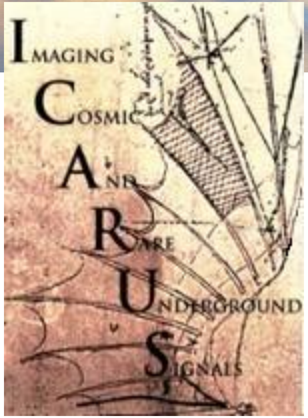


SBN Program at FNAL

Main objective**:** Confirm or rule out the existence of sterile neutrinos at the eV mass scale.

Novelty:

- Exploitation of a near and far detector system.
- Implementation of the Liquid Argon Time Projection Chamber (LArTPC) technology for both detectors.

Three LArTPCs detectors located along the Booster Neutrino Beamline:

- SBND (near detector), MicroBooNE, and ICARUS (far detector).

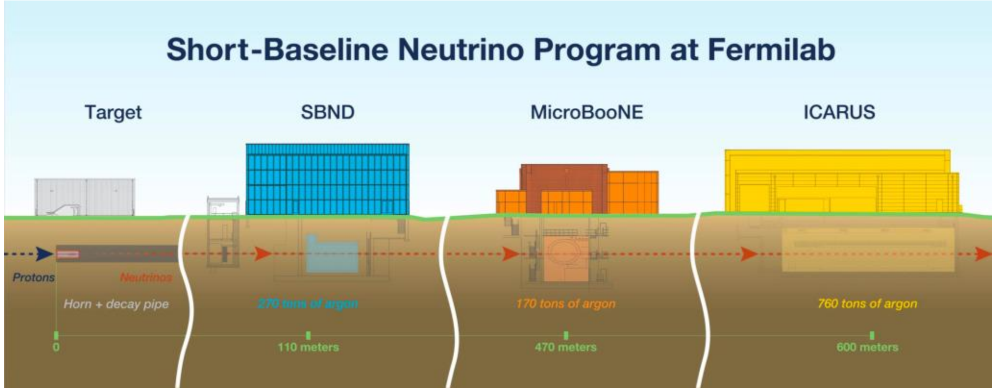


Illustration of the neutrino beamline and of the SBN detectors.

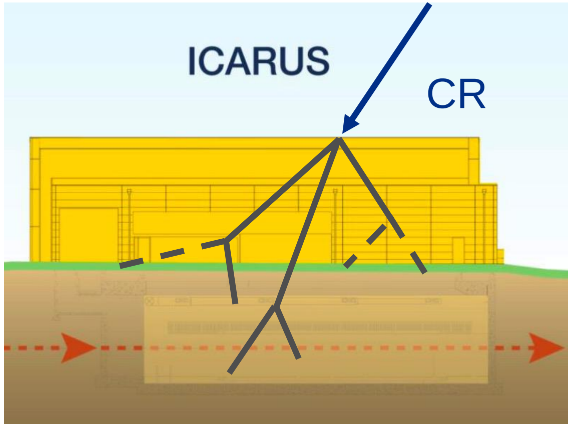
The ICARUS detector

- Four TPCs, two in each of the two cryostats (476 tons of active LAr volume)
- Located 600m from the Booster neutrino source. Operating on neutrinos from the Booster Neutrino (on-axis) and NuMI (off-axis) beams.
- The first physics run was performed between June and July 2022 (RUN1). The second physics run was between December and July 2023 (RUN2).

Left: ICARUS roof at Fermilab during the commissioning Phase. Right: ICARUS TPC during the CERN overhauling.

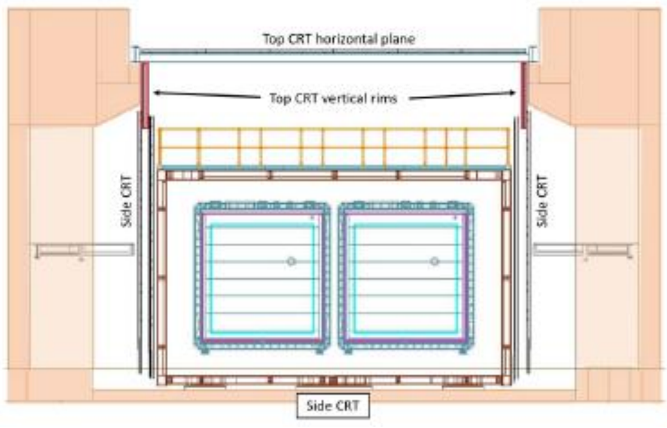
Cosmic Background at ICARUS

- Exposed to a large flux of cosmic particles (11 kHz rate in LAr sensitive volume):
  - **In time activity**: entering the detector during the BNB (1.6 μs) or NuMI (9.6 μs) neutrino beam-spill;
  - **Out of time activity**: entering during the 1 ms TPC drift time.
- Instrumented with:
  - Cosmic Ray Tagger (**CRT**) system
  - 3 m **concrete overburden** above the CRT (~7.5 m water equivalent)
    - ~20% reduction of dominant muon flux
    - Electrons and γ's almost fully suppressed
    - The suppression is also effective for hadrons, with a reduction by a factor ~ 200 of primary neutrons and ~ 500 for the protons.



The CRT System

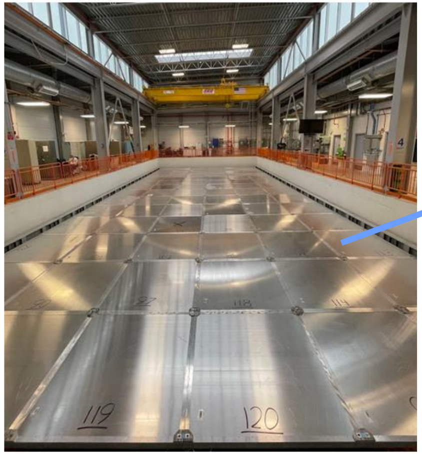
- Covers a surface area of ~1100 m^2.
- Divided in **3 different subsystems**: Top CRT, Side CRT, Bottom CRT.
- Tags cosmic ray induced events:
  - Provides **4π coverage** of the active LAr volume: possibility to identify ~95% of passing through cosmic.
  - Precise (ns scale) **synchronization** with the Photodetection system (PMT), allows discrimination between events coming form the outside the detector from those generated inside and therefore rejection of cosmic ray induced triggers.
- Top and Side CRT share a common **Front-End Board (FEB)** for the readout and biasing of the **Silicon Photo-Multipliers (SiPMs)**.
- With the FEB, the analog input signal is processed by a 32-channel integrated circuit. For each channel the chip provides charge amplification with **configurable gain**.



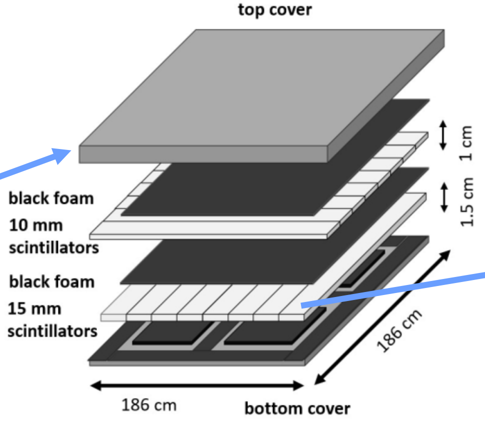
Top: Scheme of the ICARUS TPCs and CRT system modules.
Bottom: The FEB in its case.

The TOP CRT

- Commissioned and integrated into the data acquisition system in early 2022.
- Designed to intercept approximately **80% of incoming cosmic muons**.
- Composed of **123 hodoscope modules**:
  - Two orthogonal layers of eight 23 cm scintillator bars, encased in an aluminum box;
  - Each scintillator bar is instrumented with two Wavelenght Shifting (WLS) fibers embedded along the longitudinal direction.
  - The light readout is performed by Silicon Photomultipliers (SiPM) positioned at one end of each fiber.



Picture of the fully installed Top CRT.



Sketch of a Top CRT module

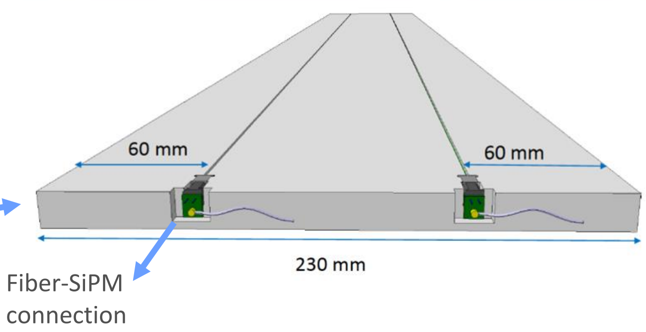


Illustration of the Fiber's disposition in the Top CRT scintillation strips.

CALIBRATION of the Top CRT (My work)

Key points of the work done:

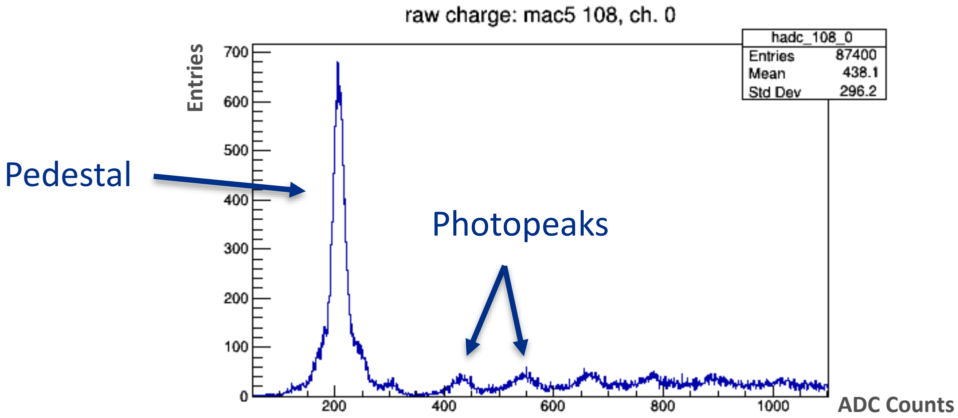
- Estimate the pedestal and SiPM gain values of each Top CRT channel;
- Develop the analysis and implement it in icaruscode, integrating it with the experiment pipeline;
- Create a function to merge large numbers of ROOT files and learn how to set up the Production Operations Management System (POMS) configuration files
- The analysis campaign runs on the files produced through POMS. For an effective calibration, at least 50k events are needed (~10 mln CRT hits).

Main goals:

- Improve the previous gain fitting algorithm;
- Build a full response spectrum of the SiPMs;
- Optimize the control on the channels' state, with an automatic and periodical calibration;
- Correct the gain parameters of the Monte Carlo simulation of the experiment.
- Determine CRT channels average light yield.

What the analysis is doing

The analysis is performed on distributions like the following:



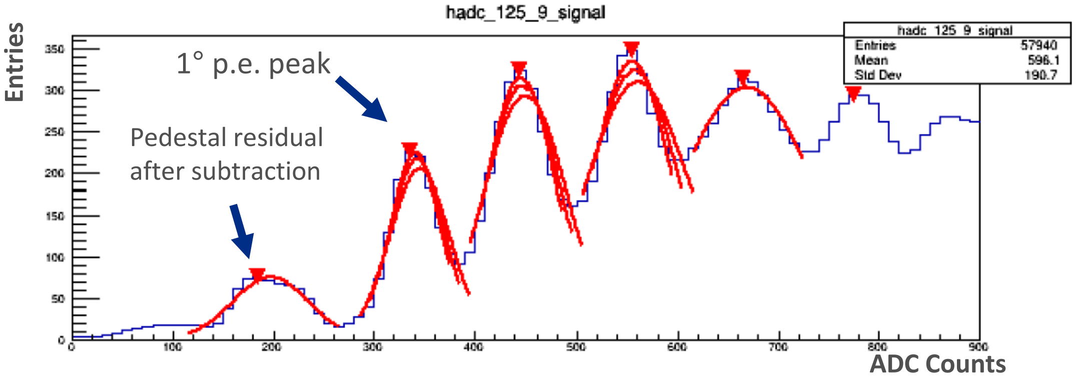
Picture: Example of spectrum for a 15 mm scintillator channel (Top Layer) zoomed in the range 0 – 1100 ADC Counts. The pedestal and signal peaks are visible.

- The SiPMs are the devices reading out light from the scintillator modules. In order to convert the units of the front-end boards from generic Analog to Digital Conversion (ADC) units to photon energies, we need to have the lower-level photopeaks visible in the spectra.
- The code looks for these peaks, and uses their ADC locations along with a calculated ”peak number”, which allows the plotting of photopeaks versus their corresponding ADC value.
- By fitting a line to these photopeak-ADC points on a graph, we can find a conversion factor for relating ADC to p.e. in that channel.

Calibration analysis (Signal)

CRT decoded data product information used	
Front-End Board MAC5 Address	fMac5
Flags representing the hit type (signal or reset hit)	fFlags
ADC values of all 32 channels of a FEB	fAdc

Data from calibration run 9989 of 6/26/2023 (~23 hours)



Picture: Example of a recursive p.e. peaks fitting for a 15 mm scintillator channel (Top Layer). The first peak is part of the pedestal, and is due to an error on the flag for some hits.

Main steps of the analysis:

- If the module has detected a signal (signal flag value 3) we take the **highest 2 ADC counts in each layer** of scintillator bars;
- Store the value in the appropriate channel's histogram;
- The ROOT function **TSpectrum** is used to **search** for the first 5 **peaks** in the hits spectrum;
- For each fit, the minimum distance between the previous and following peaks is used as the range;
- Quantized photoelectron **peaks** are **fitted recursively** using a **gaussian distribution,** adjusting the fitted range of the histogram in order to minimize the reduced χ^2

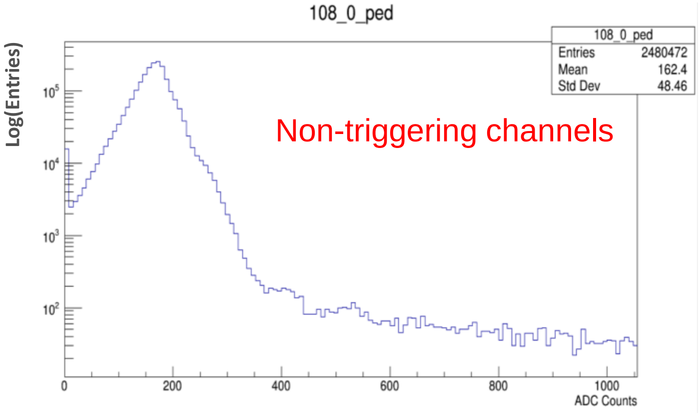
Calibration analysis (Pedestal)

With pedestal we refer to the signal distribution related to the **inherent electronic noise** in the channel.

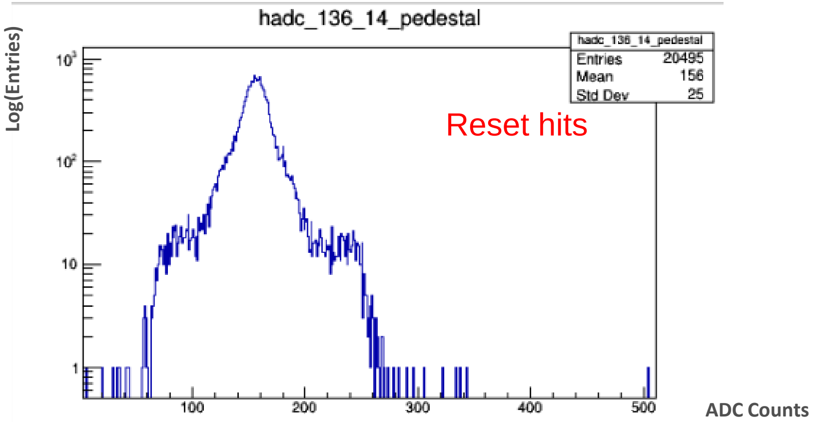
Different **selections** used to extract the pedestal from the data:

- **Non-triggering channels (fFlag equal 3):** fill the histograms excluding the highest 6 ADC values of each layer
- **Reset hits (fFlag equal 7 or 9):** use ADC values of the **T0** and **T1 special reset events** of the CRT FEB behaving as **external random triggers**.

Problem: the pedestal width is larger than the gap between two consecutive p.e. peaks;



Example of a pedestal distribution for a channel corresponding to a 15 mm bar (Top Layer) obtained with non-triggering channel logic. Source: Valerio Pia (2022)



Pedestal distribution for a Top Layer channel obtained from the reset hits, with a lower statistic.

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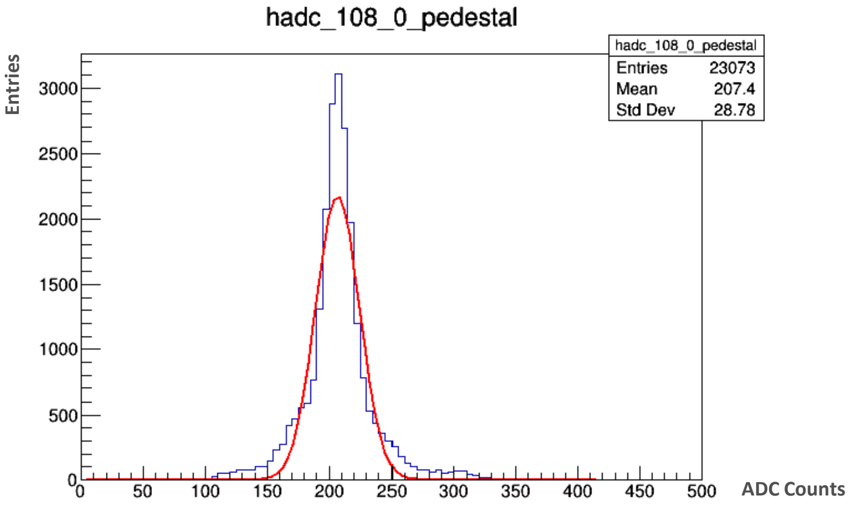
Calibration Analysis (Pedestal)

Main steps of the analysis:

- Choose a **selection method**;
- Store the ADC value in the appropriate channel's histogram;
- Perform **multiple gaussian fits**, optimizing the fit range until the reduced χ^2 is smaller than a chosen value.
- Save the **mean value of the gaussian**. This will be used in the gain evaluation.



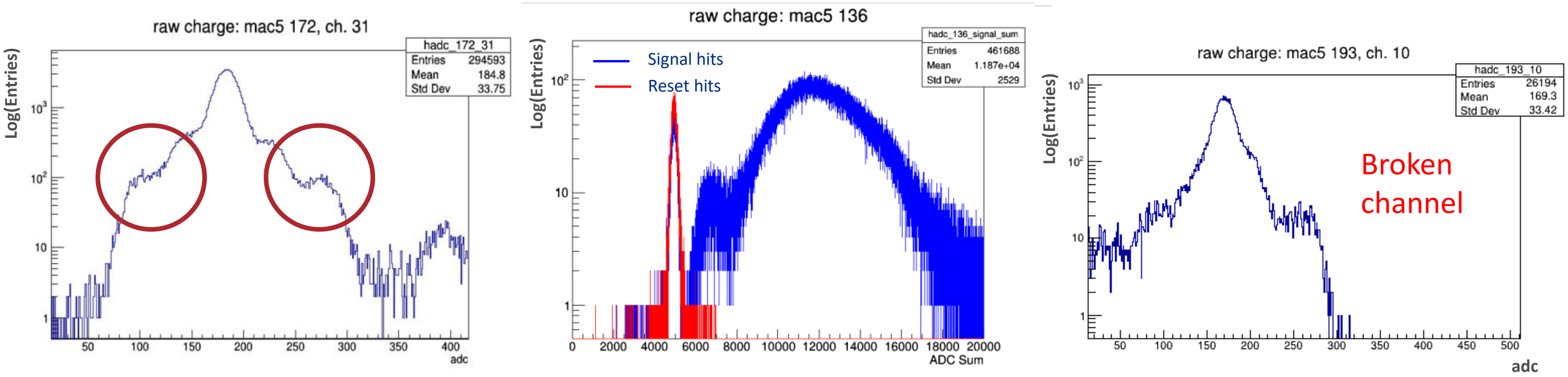
Picture: Pedestal distribution for a Top Layer channel obtained from the reset hits (blue) and gaussian fit (red) with $\chi2 < 10$.

Pedestal Estimation

Work in progress!

- The distribution for the pedesal extracted with the reset hits signal is still very large.
- Two peaks appear in the distribution:
  - Left peak: **electronic noise** generated when there's a signal hit in other channels of the same FEB
  - Right peak: could be p.e. peaks covered by pedestal or SiPM intrinsic electronic noise.

- **Possible solutions** to improve the spectrum estimation :
  - The **sum** of all the 32 ADC values for each hit can be used to separate T1/T0 reset hits from signal ones, as some reset hits are incorrectly identified as signal (known Top CRT FEBs firmware error), a cut for signal sum over 7000 will be tried;
  - Look at the **broken channels**, where no signal is detected.



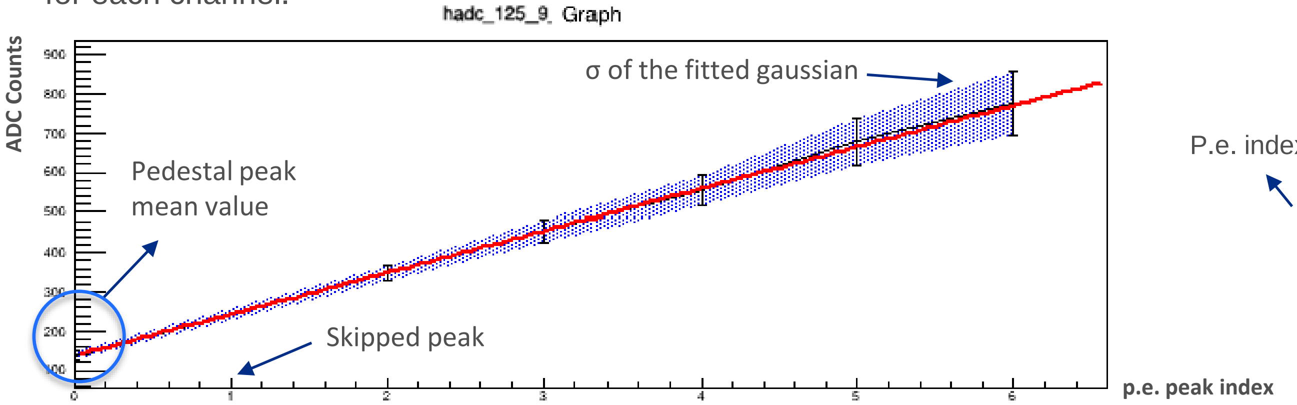
Pictures: from the left, peaks in the pedestal spectrum; superposition of the distributions of adc values sum on all 32 channels of a FEB for pedestal obtained with reset hits correctly flagged (red) and signal hits (blue); broken channel extracted signal without (no flag selection on the hit signal).

Gain fitting

- **Mean values** of the peaks are plotted **versus** the corresponding **peak number**: the **gain G** for the i-th channel is defined as the **slope** of a linear fit of the distribution.
- Some peaks were misidentified with others, introducing errors in the fit. A peak is sometimes skipped by TSpectrum and a fix for a rearrangement of the p.e. number was introduced.

Future work:

- We want to determine the average amount of light ("**light yield**") produced by the particles when they pass through scintillator bars.
- With the gain value and an adequate statistic we can obtain the distribution of the p.e. for each bar, fit and search for the peak (whose value represents the most probable number of p.e. produced per event) that is the average light yield for each channel.



ADC peak value

Pedestal mean value

P.e. index

$$n_{p.e.} = \frac{ADC_i - Ped_i}{G_{i.}}$$

Gain

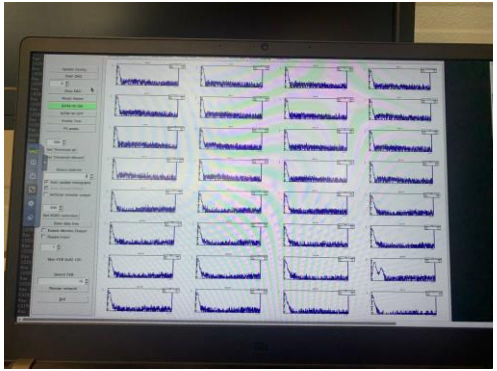
Picture: p.e. peaks mean value vs. corresponding number, after fixing the error of skipped p.e. peaks and incorrectly flagged hits;

Additional activities

During the last months I also followed and assisted the Top CRT team during the power outage routines.

Part of the job consisted in:

- turning off/on the Top CRT racks;
- rearrange the power lines to test the response of the CRT;
- check the state of all channels through the standalone DAQ, updating the list of broken channels;
- perform a powercycle when necessary;



Pictures: on the top an image of the standalone DAQ and the signal collected in real time by all channels of a specific FEB, on the bottom left the front part of the Wiener PL512 Modular Power Supply, on the bottom right a view from behind of the cables of the power lines.

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Thank you for your attention!